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# Conceptual design of 100 J cryogenically-cooled multi-slab laser for fusion research

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**Abstract.** We present a comparison of two alternative laser layouts for HiLASE and ELI Beamlines projects. The cryogenically cooled laser is 100 J class with 2 ns pulse length and operates at 10 Hz repetition rate. The laser beam is intended for industrial applications in HiLASE, for OPCPA pumping in ELI Beamlines and can serve as a test bed for large scale high repetition rate fusion lasers. First layout utilizes classical scheme with preamplifier and main amplifier, while the second layout utilizes single amplifier scheme with two amplifier heads. The comparison is based on the results obtained from homemade MATLAB code for evaluation of amplified spontaneous emission and stored energy and on a beam propagation simulated in MIRÓ code.

## 1. INTRODUCTION

Solid-state lasers are capable of delivering single-shot energy of tens of kilojoules in a single beam [1]. Emerging applications such as material processing, high energy physics, and laser driven inertial fusion will benefit from increased repetition rate of these lasers from several shots per day to several shots per second. Recently, several strategic projects on development of high energy, high average power laser systems based on multi-slab technology have emerged all over the world. Among them belong HiPER [2], LIFE [3] and ELI [4]. These planned projects aim at delivering kilojoule nanosecond pulses with repetition rates in the 10–20 Hz regime. Several smaller systems are build to test the scaling options for these high average power lasers: in USA the Lawrence Livermore National Laboratory operated the Mercury system (~60 J, 10 Hz) [5], in Japan the Institute for Laser Engineering operates the HALNA system (~20 J, 10 Hz) [6], in Germany the Institute of Optics and Quantum Electronics operates POLARIS system (12 J, 0.05 Hz) [7], in France the Laboratoire pour l'Utilisation des Lasers Intenses operates LUCIA system (10 J, 2 Hz) [8], and in United Kingdom the Rutherford-Appleton Laboratory operates DiPOLE system (6 J, 10 Hz) [9].

In Czech Republic we plan to build 100 J, 10 Hz laser system for the HiLASE and ELI Beamlines projects. The laser is intended for industrial applications in HiLASE, material processing, for pumping OPCPA in ELI Beamlines and can serve as a test bed for large scale high repetition rate lasers.

Our design of the 100 J class laser is based on cryogenically cooled Yb: YAG multi-slab technology [10]. The system consists of solid state oscillator, disk pre-amplifier and main amplifiers. In the first layout, the main amplifier consists of a 6 pass multi-slab pre-amplifier and a 4 pass power amplifier. In the second layout, the main amplifier consists of a 4 pass power amplifier with two amplifier heads.

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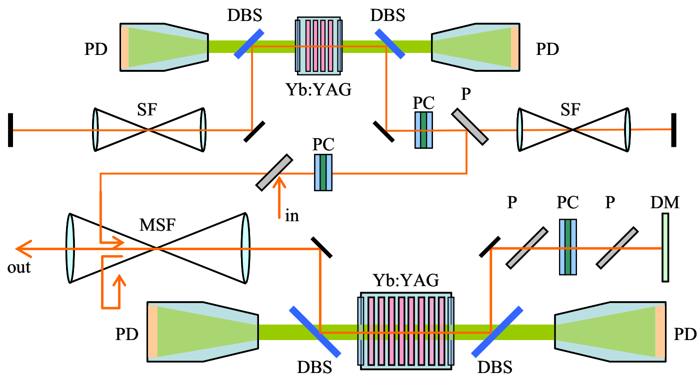


**Figure 1.** Optical layout of the laser system consisting of 10 J pre-amplifier and 100 J amplifier. Shown are amplifiers heads with laser slabs (Yb:YAG), dichroic beam splitters (DBS), pumping modules (PD), spatial filters (SF), multipass spatial filter (MFS), polarizes (P), Pockels cell (PC), and deformable mirror (DM).

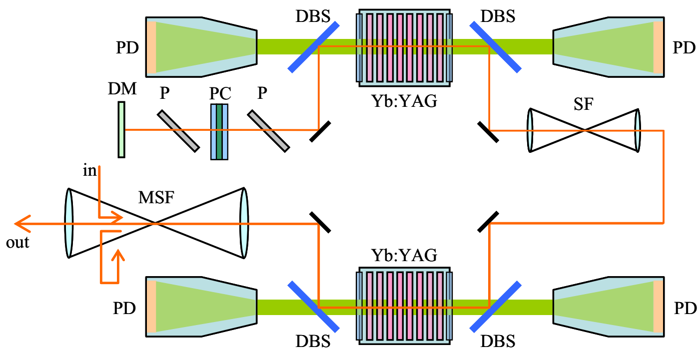


**Figure 2.** Optical layout of the 100 J laser system with two amplifier heads. Shown are amplifiers heads with laser slabs (Yb:YAG), dichroic beam splitters (DBS), pumping modules (PD), spatial filters (SF), multipass spatial filter (MFS), polarizes (P), Pockels cell (PC), and deformable mirror (DM).

The parameters of the power amplifier are chosen to allow scaling of the output laser energy to more than 500 J.

## 2. LASER LAYOUTS

The first concept of laser system consists of the 6 pass 10 J preamplifier and the 4 pass 100 J power amplifier. The design of both amplifiers is mostly similar, but the preamplifier uses polarization switching for pulse injection/ejection, while the power amplifier uses angular multi-pass scheme with 4 pinhole spatial filters. A detailed optical layout of the amplifier is shown in Figure 1. The dimensions of the laser slabs are $20 \times 20 \times 5\,mm^3$ (doping 1–2 at. %) for the preamplifier and $60 \times 60 \times 8\,mm^3$ (Yb doping 0.3–1.3 at. %) for the power amplifier.

The second concept of the laser system consists of a single 4 pass 100 J power amplifier with two similar amplifier heads. The amplifier is also angularly multi-passed as in the previous case. The detailed optical layout is in Figure 2. The dimensions of the laser slabs are $45 \times 45 \times 8\,mm^3$ (Yb doping 0.3–1.3 at.%) in both amplifiers heads.

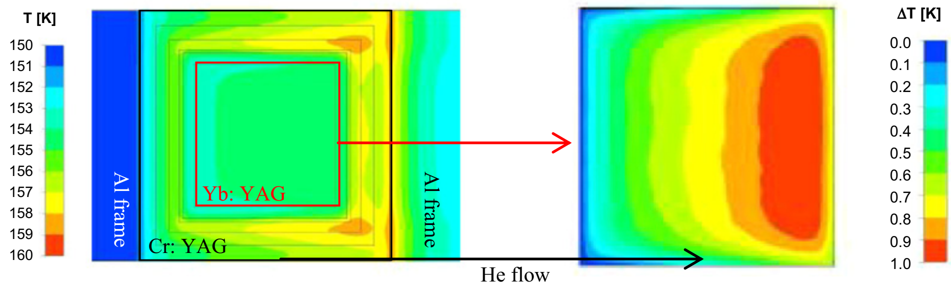


**Figure 3.** Temperature map of the surface of the Yb:YAG laser slab including the Cr:YAG absorption layer (on the left) and zoomed region of active surface of Yb:YAG (on the right) used for amplification of the laser beam that is propagating perpendicularly to the plane of the slab.

For numerical calculations we assumed that all lenses and windows in all layouts are made of BK7 glass and the optical elements have diameter of 2”, 4”, and 5” for respective beam sizes 20 mm, 45 mm, and 60 mm. They are antireflective (AR) coated with reflectivity of 0.5%. Internal transmission is assumed 100%, DKDP Pockels cell transmission is 99% and thin film polarisers transmission is 97% and reflection 99%. The thicknesses of optical components were taken either from manufacturers' standards or as 1:10 of diameter.

## 3. STORED ENERGY

In order to calculate gain of the laser amplifier we have developed a code that calculates amplified spontaneous emission in three dimensions [11]. In this program, we assume homogenous pump source, the pump photons are ray traced and absorbed in the laser slab. Then the spontaneous emission is calculated and all photons are ray traced and amplified. To limit ASE, the laser slabs are surrounded with absorptive layer of Cr: YAG. Ray tracing includes all laser slabs and AR coating on all interfaces. The material cross-sections were obtained experimentally for temperature of 160 K [12].

The first laser system was pumped by intensity of 5 kW/cm$^2$ from both sides of the amplifier in 1 ms pulse at 938 nm @ 6 nm FWHM. The stored energy for the preamplifier was 20 J out of 40 J and for the power amplifier 192 J out of 360 J. The stored energy efficiency was 52%. The second laser system was pumped with lower intensity to limit the amplification to 100 J, the pump intensity was 4.3 kW/cm$^2$ and the stored energy was 96 J out of 172 J in each amplifier head. The stored energy efficiency was 56%.

## 4. COOLING CONSIDERATIONS

The laser slabs are cooled by forced flow of He gas with temperature of 150 K. To obtain temperature distribution in the crystal by finite elements method and hydrodynamic calculation, we used heat source deposition map obtained in the ASE calculation code. The calculation was done in ANSYS by CEA SBT Grenoble [13]. The calculation predicts less than 2 K variation of the slab temperature. The code was experimentally benchmarked in classical regime and showed accuracy of 0.1 K. The surface temperature of the slab is shown in Figure 3.

## 5. BEAM PROPAGATION

With the known gain of the amplifiers, we propagated beam through the amplifier with the MIRÓ program. The input pulse energy and shape was optimized and yield 200 mJ in semi triangular pulse (amplitude increases along the pulse). Such a pulse will have flat-top shape at the output of the amplifier.

The beam shape had super Gaussian profile of 8th order and filled the active area of the amplifier from ~85 % in order to minimize diffraction effects.

In the 10 J pre-amplifier, the input pulse energy of 200 mJ was amplified to almost 9 J, and after that it was increased to 105 J in the main amplifier. The average output fluence was 2.5 J/cm$^2$, while the peak fluence caused by diffraction effects slightly exceeded 5 J/cm$^2$. The maximum B-integral per section between spatial filters was almost 1.0 rad and the overall accumulated B-integral was close to 2.5 rad. Optical-to-optical efficiency of the system was nearly 26%.

In the second system, the 200 mJ input energy was amplified to 101 J in the main amplifier with two amplifier heads. The average output fluence was 5 J/cm$^2$ and the peak fluence was 8.5 J/cm$^2$. Higher operating fluence increased the maximum B-integral per section between spatial filters to 1.15 rad and the overall accumulated B-integral to 3.0 rad. However, the optical-to-optical efficiency of the system increased to 28%.

## 6. SUMMARY

We have compared two laser systems suitable for production of 100 J laser pulses at 10 Hz repetition rate. The first system consisted of 10 J pre-amplifier and 100 J amplifier with lower B integral values and less fluence on optical components. The second system consisted of a single amplifier with two laser heads. It gave similar output energy with higher efficiency and higher risk of laser-induced damage.

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